ADA

BRAKE FLUID COMPATIBILITY WITH HARDWARE

INTERIM REPORT
TFLRF No. 445

By
Douglas M. Yost

U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

For
Jill M. Bramer
U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. W56HZV-09-C-0100 (WD17-Task 6)

May 2014

Disclaimers

Contracted Author

DTIC Availability Notice

Disposition Instructions

BRAKE FLUID COMPATIBILITY WITH HARDWARE

INTERIM REPORT
TFLRF No. 445

By
Douglas M. Yost

U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

For
Jill M. Bramer
U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. W56HZV-09-C-0100 (WD17-Task 6)
SwRI® Project No.: 08.14734.17.230

UNCLASSIFIED: Distribution Statement A. Approved for public release

May 2014

Approved by:

Gary B. Bessee, Director
U.S. Army TARDEC Fuels and Lubricants
Research Facility (SwRI®)

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**			
1. REPORT DATE *(DD-MM-YYYY)* 05/19/2014	**2. REPORT TYPE** Interim Report		**3. DATES COVERED** *(From - To)* June 2011 – May 2014
4. TITLE AND SUBTITLE BRAKE FLUID COMPATIBILITY WITH HARDWARE			**5a. CONTRACT NUMBER** W56HZV-09-C-0100
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Yost, Douglas			**5d. PROJECT NUMBER** SwRI 08.14734.17.230
			5e. TASK NUMBER WD 17 (Task 6)
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI®) Southwest Research Institute® P.O. Drawer 28510 San Antonio, TX 78228-0510			**8. PERFORMING ORGANIZATION REPORT NUMBER** TFLRF No. 445
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army RDECOM U.S. Army TARDEC Force Projection Technologies Warren, MI 48397-5000			**10. SPONSOR/MONITOR'S ACRONYM(S)**
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION / AVAILABILITY STATEMENT UNCLASSIFIED: Dist A Approved for public release; distribution unlimited			
13. SUPPLEMENTARY NOTES			
14. ABSTRACT This task evaluated the compatibility of Army Silicone Brake Fluid (MIL-PRF-46176B, DOT V, SAE J 1705) with a commercial Heavy Duty Anti-Lock brake system. There have been reports of possible high temperature degradation of the MIL-PRF-46176B, DOT V, brake fluid that have led to deposition and filter plugging, and subsequent braking system filter collapse. Testing of a Hydraulic Power Brake system with MIL-PRF-46176 silicone brake fluid confirmed a manufacturer claim that the fluid was incompatible with the power brake hardware. Testing with a DOT III brake fluid did not reveal any evidence of particulate formation.			
15. SUBJECT TERMS Hydraulic Power Brake, Anti-lock, Brake Fluid, DOT III, DOT V, MIL-PRF-46176, deposition			

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	Unclassified	27	19b. TELEPHONE NUMBER *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

EXECUTIVE SUMMARY

This task evaluated the compatibility of Army Silicone Brake Fluid (MIL-PRF-46176B, DOT V, SAE J 1705) with a commercial Heavy Duty Anti-Lock brake system. There have been reports of possible high temperature degradation of the MIL-PRF-46176B, DOT V, brake fluid that have led to deposition and filter plugging, and subsequent braking system filter collapse.

Heavy-Duty hydraulic anti-lock brake systems utilize pumps, accumulators, and high-speed servo valves to regulate hydraulic braking pressure to individual wheel braking circuits. The system components and working fluid utilized for the braking circuits are also similar to the components that may be utilized for hydraulic semi-active suspension systems.

Testing of a Hydraulic Power Brake system with MIL-PRF-46176 silicone brake fluid confirmed a manufacturer claim that the fluid was incompatible with the power brake hardware. Using a pump and dump approach that exercised the servo valves and hydraulic pumps, particulate laden fluid was evident on the internal filter at 7,000 cycles. Silicone brake fluid testing continued to 20,000 cycles where the filter element appeared caked with particles and the testing was terminated. The filter media had not failed, nor was the effect of failed media and particle incursions on the pumping elements and servo valves determined. Testing with DOT III fluid to 20,000-cycles did not reveal any evidence of particulate formation.

Recommendations include determining further analytical procedures available for examination of the MIL-PRF-46176 residue and the new and used brake fluids. Investigations of Hydraulic Power Brake system elastomers and pumping elements are also recommended.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period June 2011 through May 2014 under Contract No. W56HZV-09-C-0100. The U.S. Army Tank Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Eric Sattler (RDTA-SIE-ES-FPT/MS110) served as the TARDEC contracting officer's technical representative. Ms. Jill Bramer of TARDEC served as project technical monitor. Mr. Daniel Watson of TARDEC designed the test stand fixtures and specified the wiring and hydraulic circuit components for the test bench.

The authors would like to acknowledge the contribution of the TFLRF technical and administrative support staff.

TABLE OF CONTENTS

Section **Page**

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

DC	Direct Current, amps
DOT	Department of Transportation
ECU	Electronic Control Unit
EOT	End of test
FTIR	Fourier Transform Infra-Red
GC-MS	Gas Chromatography-Mass Spectroscopy
HCU	Hydraulic Control Unit
HPB	Hydraulic Power Brake
HPLC	High Pressure Liquid Chromatography
IR	Infra-Red
kW	Kilowatt, power
L	Liters
L/min	Liters per minute
LFPSI	Left Front Brake Circuit Pressure
LRPSI	Left Rear Brake Circuit Pressure
mg/L	Milligrams per liter
MIL-PRF-46176	Military Silicone Brake Fluid Specification
min	Minute
mL/min	Milliliters per minute
NDA	Non-Disclosure Agreement
PC	Personal Computer
PET	Polyethylene Terephthalate, clear plastic
ppm	Parts per million
PRISM	SwRI Data Acquisition and Control System
psi	Pounds per square inch
psig	Pounds per square inch, gauge
QPL	Qualified Products List
RFPSI	Right Front Brake Circuit Pressure
RRPSI	Right Rear Brake Circuit Pressure
SAE	Society of Automotive Engineers
SEM	Scanning Electron Microscope
SwRI	Southwest Research Institute
TARDEC	Tank-Automotive Research, Development, and Engineering Center
TFLRF	TARDEC Fuels and Lubricants Research Facility
W	Watt, power

1.0 BACKGROUND

This task evaluated the compatibility of Army Silicone Brake Fluid (MIL-PRF-46176B, DOT V, SAE J 1705) with a commercial Heavy Duty Anti-Lock brake system. There have been reports of possible high temperature degradation of the MIL-PRF-46176B, DOT V, brake fluid that have led to deposition and filter plugging, and subsequent braking system filter collapse.

Heavy-Duty hydraulic anti-lock brake systems utilize pumps, accumulators, and high-speed servo valves to regulate hydraulic braking pressure to individual wheel braking circuits. The system components and working fluid utilized for the braking circuits are also similar to the components that may be utilized for hydraulic semi-active suspension systems.

2.0 INTRODUCTION AND OBJECTIVES

The task approach was to design and set-up an Anti-Lock brake test system that would integrate a Hydraulic Power Brake (HPB) test system to evaluate brake fluid performance. A DOT III brake fluid was used as the Reference Fluid along with the evaluation of the MIL-PRF-46176 (DOT V, SAE J 1705) Silicone brake fluid. Components were evaluated for any deposits and particle accumulations. The DOT III brake fluid was purchased as a commercial product from CSD Inc., of Conroe TX. The MIL-PRF-46176 brake fluid was purchased and received from the approved QPL supplier, CSD Inc., of Conroe, TX.

TFLRF staff along with TARDEC personnel visited the brake system manufacturer to discuss military specification silicone brake fluid issues in the Hydraulic Power Brake (HPB) and Hydraulic Control Unit (HCU). The manufacturer is a US/German joint venture company, and the HPB units are manufactured in Hanover, Germany. Both halves of the joint venture have performed tests with DOT V silicone brake fluids. Manufacturer staff were very familiar with the DOT V silicon brake fluid issues as they had performed the in-house experiments, and were open about sharing information and were pleased that TARDEC had taken an interest in the silicone brake fluid issues. A Non-Disclosure Agreement (NDA) between SwRI and the manufacturer was established, and the technical information required to perform testing was provided to

TFLRF. The testing suggested by the manufacturer was a simplified approach to the testing detailed in test reports provided earlier by the manufacturer. TFLRF staff visited a lab and saw the test setup as previously used, which was extremely simple. In essence, the hydraulic system is exercised by performing an accumulator dump that vents the brake fluid across an orifice back to the reservoir, which then triggers the Electronic Control Unit (ECU) to turn on the pump motors to raise the system pressure again. It is the cycling of the dump and pump that appears to degrade the brake fluid. A wiring diagram, some connectors, and a copy of the service tool software were provided to TFLRF. An additional software module, plus a component part number list and price quote was provided once the NDA was executed.

3.0 TEST ARTICLES

The Hydraulic Power Brake unit consisted of several integrated mechanical components controlled by an Electronic Control Unit. The HPB unit had independent front and rear braking circuits. Each braking circuit had an electric motor that drove a pumping element to maintain braking pressure, a gas charged accumulator to store circuit pressure, and a pressure transducer for measurement and control. Each circuit had two independent wheel circuits, right and left, which had two servo valves for each wheel. One of the wheel servo valves controlled pressurized fluid to the brake calipers, while the second servo valve was responsible for anti-lock or brake release action by relieving caliper circuit pressure back to the reservoir. Brake circuit action was initiated by pressure from the master cylinder through relay valves. The ECU monitored the system pressures and controlled the motors to maintain accumulator pressure, controlled the servo valves based on relay valve action, and controlled anti-lock action based on wheel speed sensors. A service software tool was utilized to control the HPB on the test bench without the need for wheel speed sensors.

A “pump and dump” charging scheme was identified by the HPB manufacturer as a way to cycle the brake fluid to develop deposits in a shortened time interval. The control software was used to dump the accumulator pressure, through small orifices, shearing the fluid, back into the reservoir, which then initiated a pumping cycle to regenerate the accumulator(s) pressure. The “pump and dump” cycle was repeated until deposition occurred and the pump inlet filter mesh screen collapsed. A window was machined into the hydraulic reservoir to allow visual access to the filters so that deposition could be monitored. A Noregon JPRO Data Link Adaptor was obtained to communicate with the HPB system ECU through the service software running on a laptop PC. The stand was also designed to utilize stroking of a master cylinder to initiate accumulator drawdown and subsequent pump operation. Manufacturer documentation suggested thirty strokes of the master cylinder should deplete the hydraulic accumulators and initiate subsequent pump operation. TARDEC Force Projection Team staff visited TFLRF and designed the test frame for the brake system components, designed the wiring harness, and specified all hydraulic circuitry components.

TFLRF obtained the auxiliary items and instrumentation required to operate the power brake systems and to record HPB system data. Brake fluid compatible window and sealant materials were sought before the pump and dump operation was initiated. The initial window material, polymethyl methacrylate, failed due to stress cracking when it came in contact with the DOT III brake fluid. A Polyethylene Terephthalate (PET) material appears to have good compatibility with DOT III and DOT V brake fluids. The HPB test stand is shown in Figure 1.

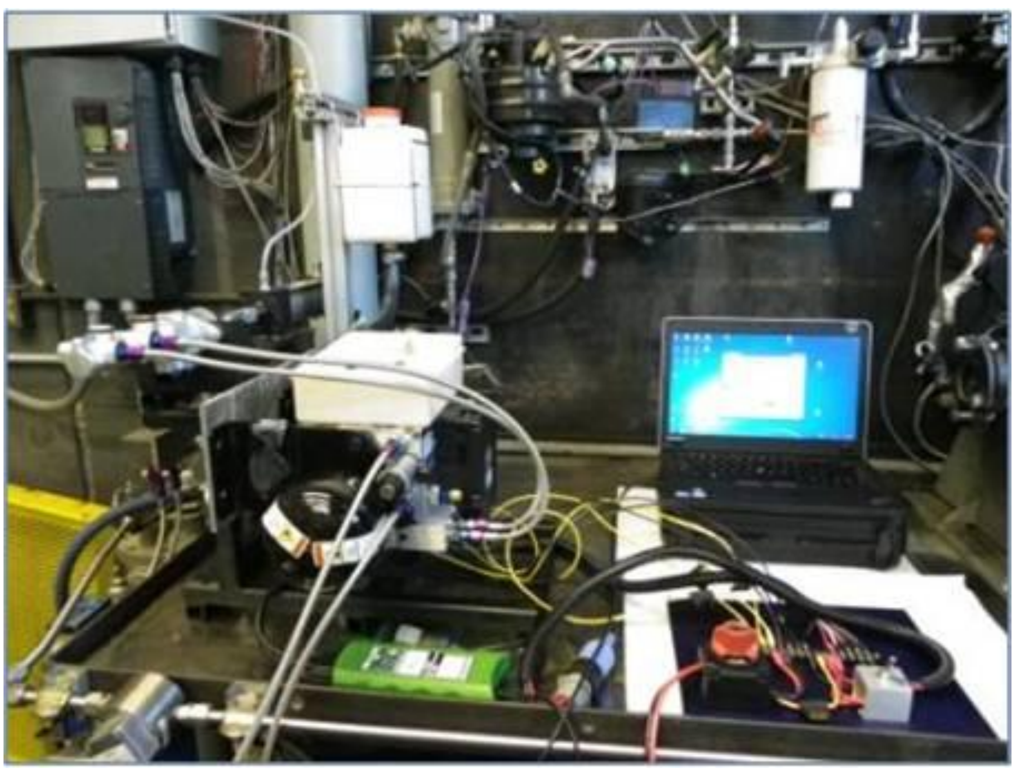


Figure 1. Hydraulic Power Brake Unit Test Stand

A PET window material and a two-part epoxy adhesive compatible with both brake fluids, the poly-propylene reservoir, and PET was used to bond the window to the hydraulic fluid reservoir. There was not any initial evidence of stress cracking of the window material or leakage from the window adhesive bonding due to the presence of the DOT III brake fluid.

The custom version of the service software had a hidden utility to activate the motor and accumulator cycling. A single-shot accumulator dump function in the software allowed TFLRF to exercise the brake system in order to validate the control programming and data acquisition system. The HPB system was instrumented and wired into the SwRI PRISM data acquisition and control system, and the PRISM control sequences were programmed. Data channels included each of the four braking circuit pressures (LFPSI, RFPSI, LRPSI, RRPSI), motor bus voltage, each motor current, and fluid temperatures. The motor power was calculated as the product of the DC motor bus voltage and the individual DC motor currents.

Figure 2 is a representative plot of brake circuit pressures and motor power during the dump and pump cycle triggered by the service software. This cycle repeated fairly regularly, but was almost four minutes in duration. At the completion of the motor pressurization cycles, the system dwelled for over a minute, then turned each motor on to make sure the accumulator system pressure was up, then about thirty seconds later it dumped the accumulators. The system initially dumped pressure to the front brake circuit, then the rear, then bled the pressure back to the reservoir. The motors turned on after the initial pressure dump to recharge the accumulators, they ran about 40-50 seconds. Then the cycle started over. These traces were with DOT III fluid, and a representative DOT V trace was identical.

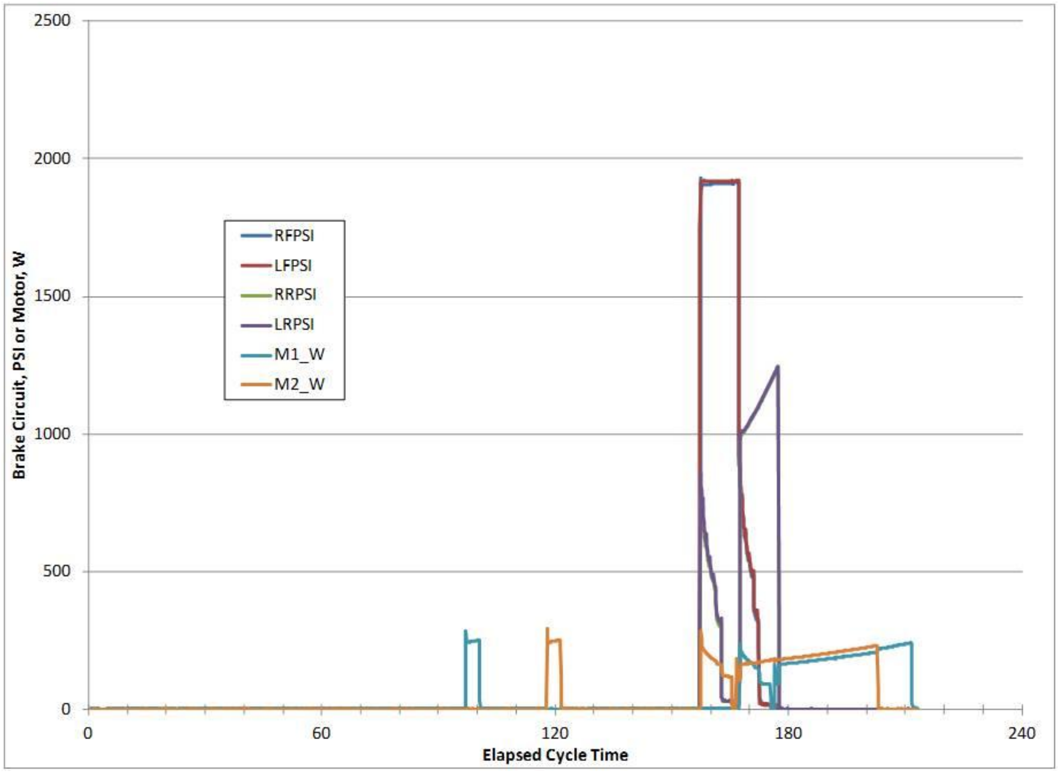


Figure 2. Hydraulic Power Brake System Pump and Dump Motor and Pressure Histories

When the accumulator pressure blew down to the reservoir, there were turbulent flow and pressure spikes. These pressure fluctuations compromised the window sealing on the reservoir and brake fluid leaked from the system. The window was cut too close to one of the bolts, and there was not enough surface area for an adequate bond. The window material and epoxy appeared to be compatible with the DOT III fluid. The window arrangement with the reservoir was reconfigured to allow for more sealing surface area, and better surface preparation for the epoxy.

All brake fluid was removed from the current system in order to plumb in the master cylinder with fluid reservoir. The master cylinder with reservoir was raised higher, to re-position the master cylinder such that a line could connect to the HPB reservoir without a low spot, and so the existing thermocouple could be used. The master cylinder was installed, tightened, and, connected to the stroking air cylinder as shown in Figure 3.

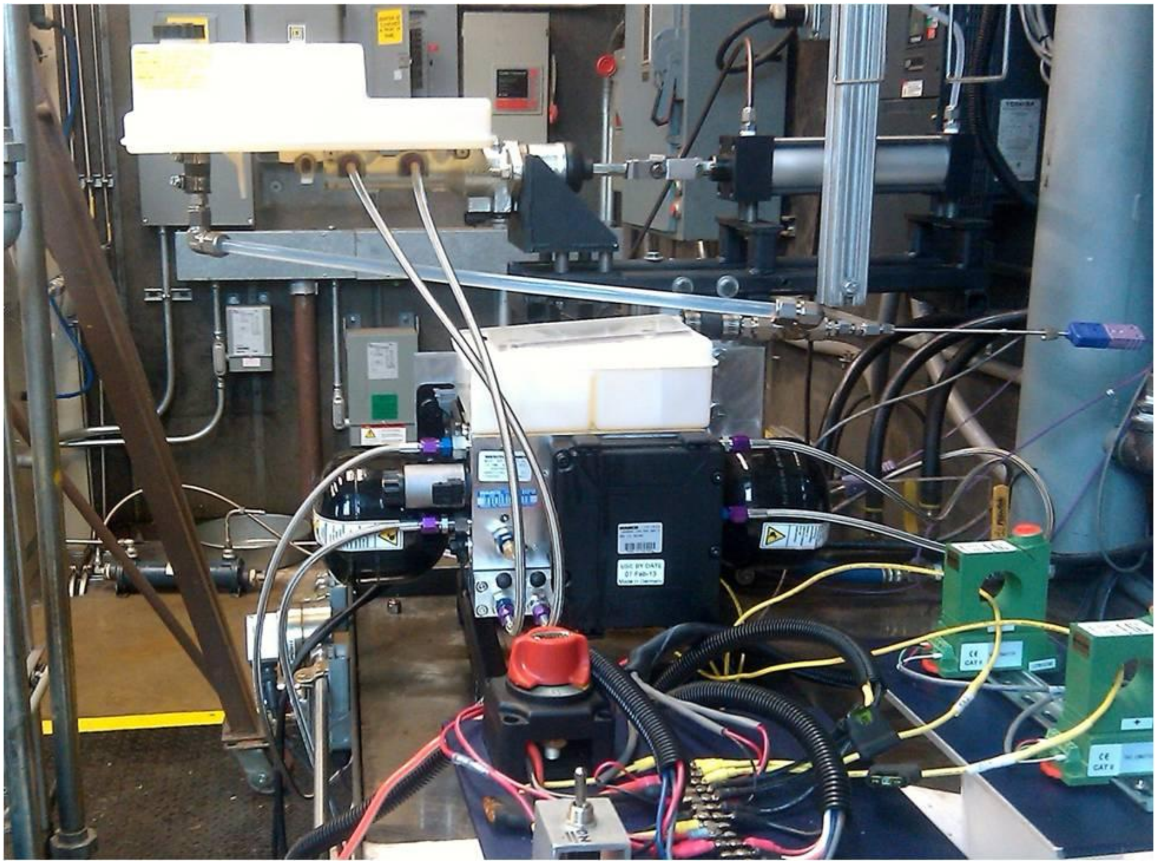


Figure 3. Hydraulic Power Brake System with Master Cylinder with Reservoir and Stroking Cylinder

An HPB fluid reservoir was modified with a significantly smaller opening for observing deposition on the filter media. Before cutting the new opening in the spare HPB reservoir, the top surface of the reservoir was lightly sanded with a belt sander. The light sanding eliminated waviness of the reservoir surface for better window contact, and roughened up the HPB reservoir surface for better epoxy adhesion. New windows were machined for the reservoir, with the clear plastic outside of the cut-out area roughened with sandpaper for better epoxy adhesion between the window and reservoir.

The window was adhered to the reservoir and the HPB pump and dump control was initiated with the DOT III fluid to test system integrity. After 1100 pump and dump cycles the adhesive between the reservoir and the window failed. The brake fluid temperature in the reservoir increased due to the pumping and shearing actions, which appeared to compromise the strength of the adhesive bond. A mechanical clamping arrangement with the PET window and a gasket material was designed. A clamping plate that bears on the molded reservoir flange and a crossbar was used to secure the window to the fluid reservoir. A thin rubber gasket was also used between the window and the reservoir, along with large fender washers below the reservoir bolts to evenly distribute the clamping force across the window. The clamping plate and crossbar can be seen in Figure 4. The clamping arrangement proved advantageous for allowing access for inspecting the filter media during testing with the brake fluids, specifically for the dyed DOT V fluid.

Figure 4. Clamping Arrangement for Hydraulic Power Brake Reservoir Window

The DOT III brake fluid was used to set up the HPB system, troubleshoot the control system, and refine the test methodology. Using the DOT III fluid it was determined the pump and dump control approach resulted in greater pressure fluctuations and more motor operational time than a master cylinder, brake application approach. Through all troubleshooting events, there were approximately 1500 pump and dump counts accumulated for the DOT III fluid. In previous manufacturer testing, the HPB system has always remained clean with DOT III brake fluid, which is a fluid certified for the system. Figure 5 shows one of the HPB filter meshes for the DOT III fluid that appears clean. The image was obtained using a video bore scope to inspect the filter meshes. Any flaky debris on the mesh is either plastic from the window cut out or residual epoxy from the initial attempts to glue the window to the reservoir. There is evidence of adhesive (Figure 5, lower left) on the mesh from the filter assembly manufacturing process.

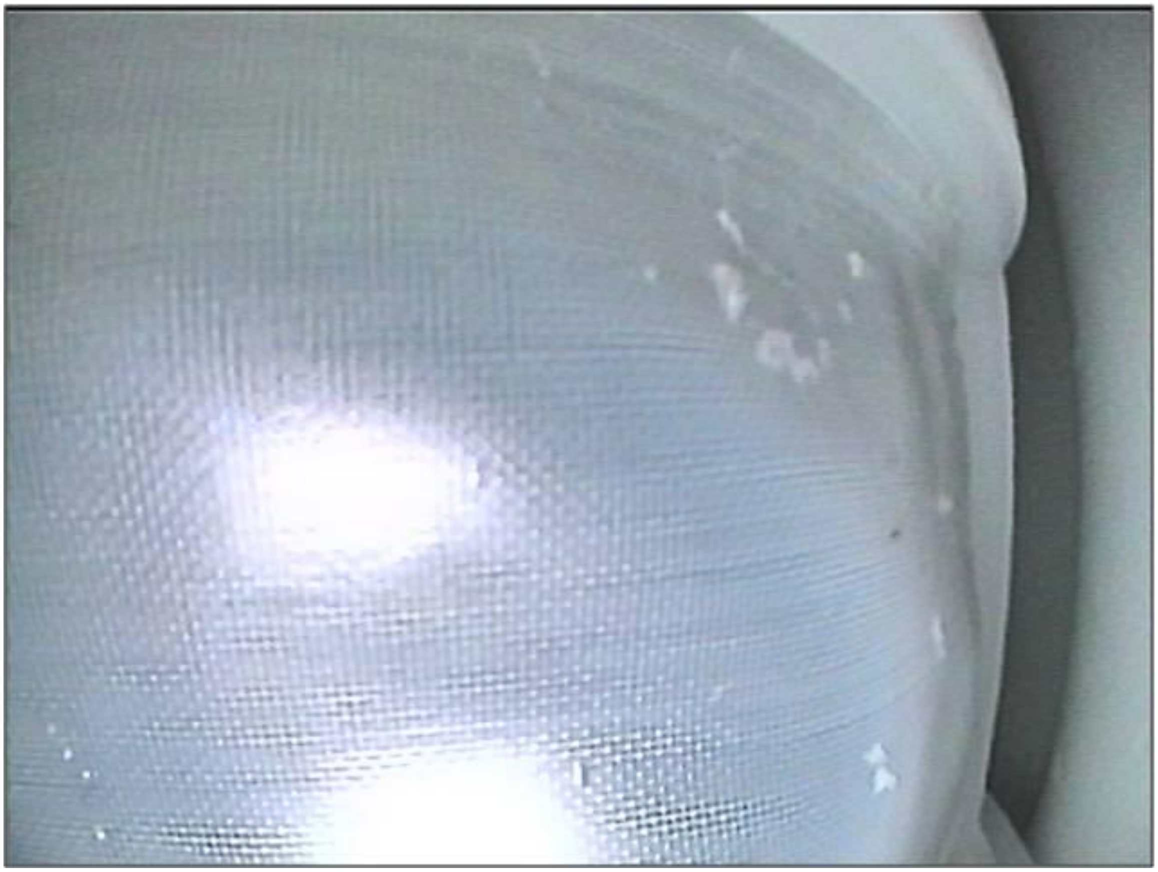


Figure 5. Clean DOT III Filter Mesh After 1500-cycles

The DOT III testing was terminated because previous testing by the manufacturer indicated the fluid does not break down, but the DOT V fluid would generate particles in a relatively short time interval. It was decided to proceed with DOT V testing, determine the number of cycles till fluid break down, and then run the DOT III fluid to the same number of cycles and evaluate for fluid break down.

4.0 EVALUATIONS, DISCUSSIONS, AND RESULTS

4.1 DOT V BRAKE FLUID (MIL-PRF-46176)

The DOT V brake fluid was tested in a second HPB system that had not been previously filled with DOT III fluid. In the likelihood that DOT III fluid had been used by the manufacturer to validate the system build remained, several flush and drain cycles of the accumulators and reservoirs were performed. The HPB system was filled with DOT V fluid and entrapped air bled off. Testing commenced with the DOT V fluid utilizing the service software to control the pump and dump action of the HPB system. The DOT V fluid is dyed purple, such that the filter screens are not visible through the window during operation. To inspect the filter screens the system is halted, window and clamp removed, the DOT V test fluid is removed and reserved, and the filter screens are inspected. After filter screen inspection the window and clamp are reinstalled and the reserved DOT V test fluid is returned to the reservoirs.

After 7,000 pump and dump cycles were accumulated with the DOT V fluid it was noted a dark viscous fluid appeared to cover the filter mesh, but particulate did not appear evident. There was not any evidence of particulate formation plugging the filter screens. There did appear to be an “ink-like” viscous fluid on the screens that was believed to be the dye for the fluid. A sample of the “ink-like” fluid was scraped off a section of the HPB filter media and onto a glass fiber filter paper as shown in Figure 6. Examination under a microscope revealed dark and metallic particles were suspended in the thickened liquid, Figure 7.

Figure 6. Scraping from HPB Media of Thickened DOT V Fluid after 7,000 Cycles

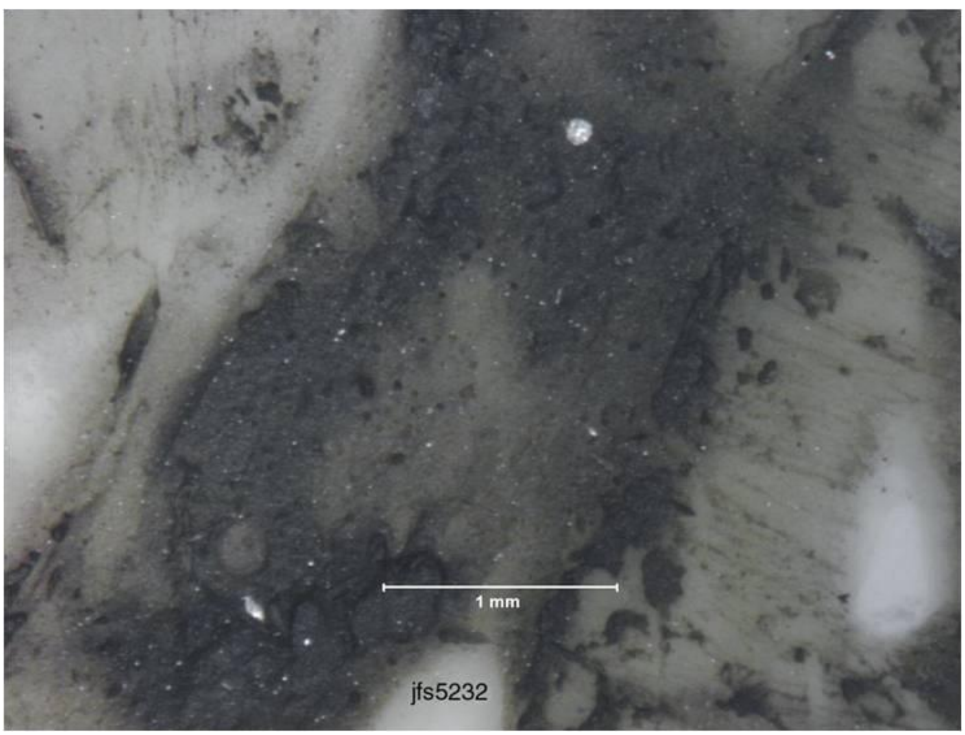


Figure 7. Filter Patch After 7,000 cycles Revealing Dark and Metallic Particles

Elemental analysis reports of the deposits and particles noted on the backscatter SEM image shown in Figure 8 are included as Figure 9 for the jfs9176 surface scan, and as Figure 10 for the jfs9177 particle scan. The surface appears to be primarily silicon, and the particle is primarily silicon and iron. Testing was continued because the filter media in the hydraulic reservoir did not appear compromised.

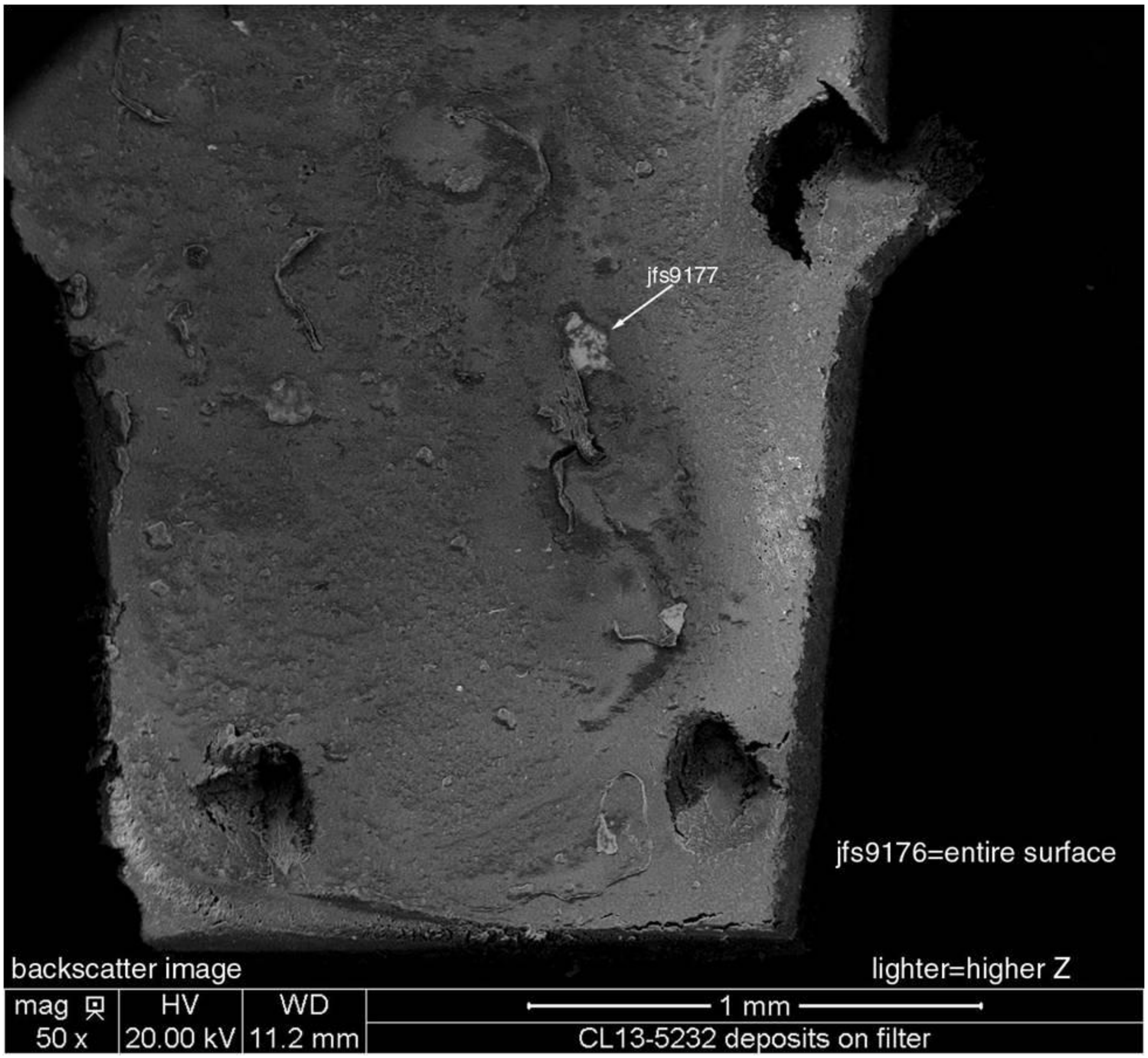
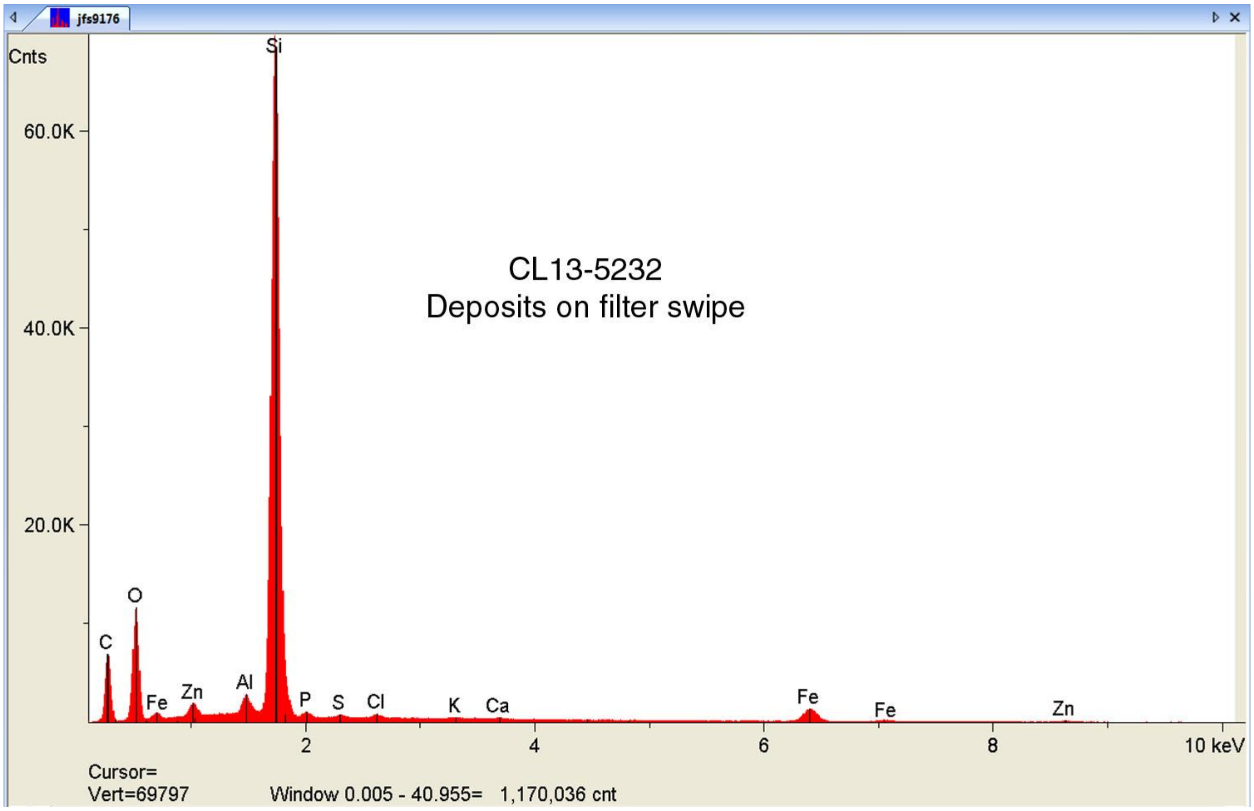


Figure 8. Backscatter SEM Image showing Elemental Analysis Scan Locations

Analysis Report: jfs9176



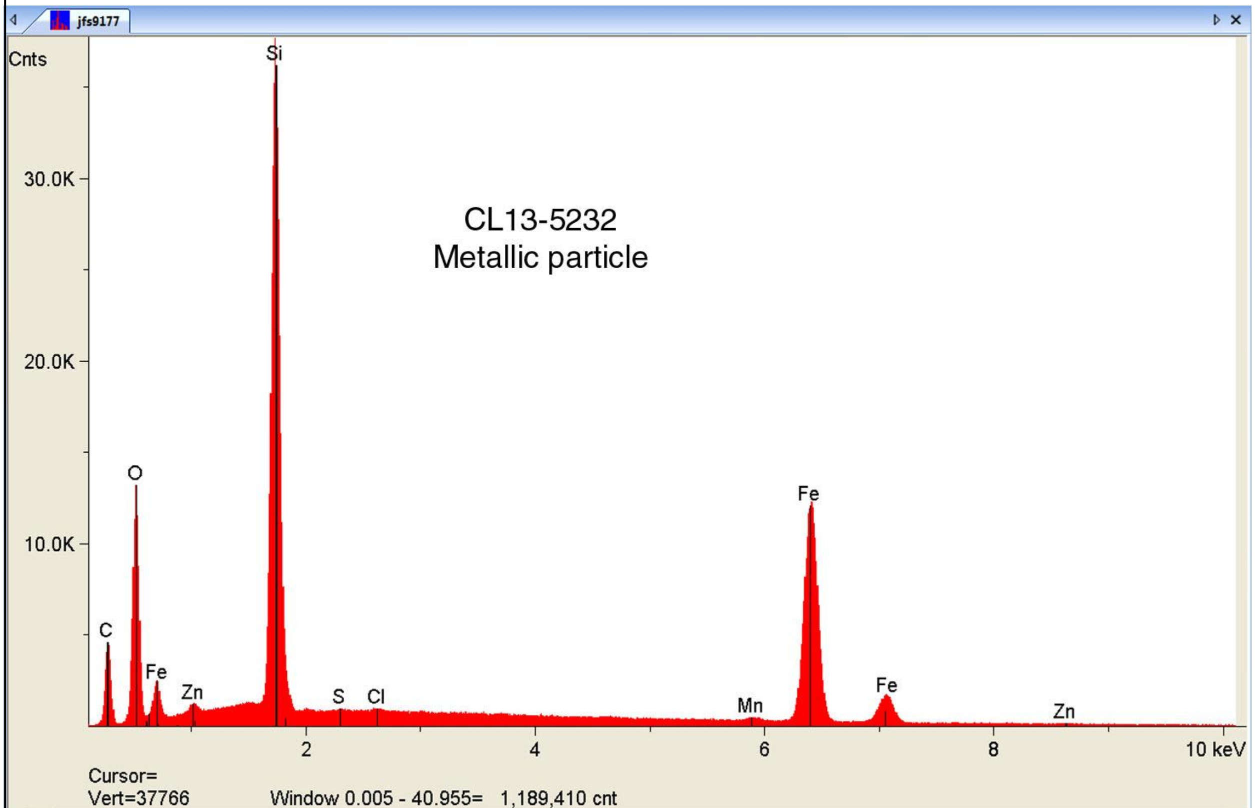
Elt.	Line	Intensity (c/s)	Atomic %	Conc	Units	
Al	Ka	57.17	2.55	2.33	wt.%	
Si	Ka	2,019.68	89.46	84.98	wt.%	
P	Ka	12.47	1.39	1.46	wt.%	
S	Ka	9.25	0.76	0.83	wt.%	
Cl	Ka	11.65	0.77	0.93	wt.%	
K	Ka	5.47	0.28	0.37	wt.%	
Ca	Ka	5.84	0.28	0.39	wt.%	
Fe	Ka	61.10	3.79	7.15	wt.%	
Zn	Ka	6.49	0.71	1.58	wt.%	
			100.00	100.00	wt.%	Total

kV 20.0
Takeoff Angle 23.0°
Elapsed Livetime 300.0

Note: Results do not include elements with Z<11 (Na).

Figure 9. Surface Scan jfs9176 Elemental Analysis

Analysis Report: jfs9177



Elt.	Line	Intensity (c/s)	Atomic %	Conc	Units	
Si	Ka	1,079.54	66.15	49.75	wt.%	
S	Ka	5.44	0.36	0.31	wt.%	
Cl	Ka	7.20	0.39	0.37	wt.%	
Mn	Ka	9.16	0.46	0.68	wt.%	
Fe	Ka	569.97	32.34	48.36	wt.%	
Zn	Ka	2.86	0.31	0.54	wt.%	
			100.00	100.00	wt.%	Total

kV 20.0
Takeoff Angle 23.0°
Elapsed Livetime 300.0

Note: Results do not include elements with Z<11 (Na).

Figure 10. Particle Scan jfs9177 Elemental Analysis

Testing was continued until 11,000 pump & dump cycles were accumulated on the DOT V brake fluid. Again there was no evidence of particulate formation in the HPB reservoir. However the thickened fluid evident at 7,000 cycles was also present, and appeared to be heavier, but did not appear to compromise the filter media. Another scraping was made of the thick fluid, and transferred to glass fiber filter media. The thickened fluid at 11,000 cycles is shown in Figure 11.

Figure 11. Scraping from HPB Media of Thickened DOT V Fluid after 11,000 Cycles

The filter patch, Figure 12, was examined under a microscope and revealed dark and metallic particles. An elemental analysis report of the deposits and particles is included as Figure 13 for the jfs9178 surface scan. The surface appears to be primarily silicon, and testing was continued because the filter media did not appear compromised.

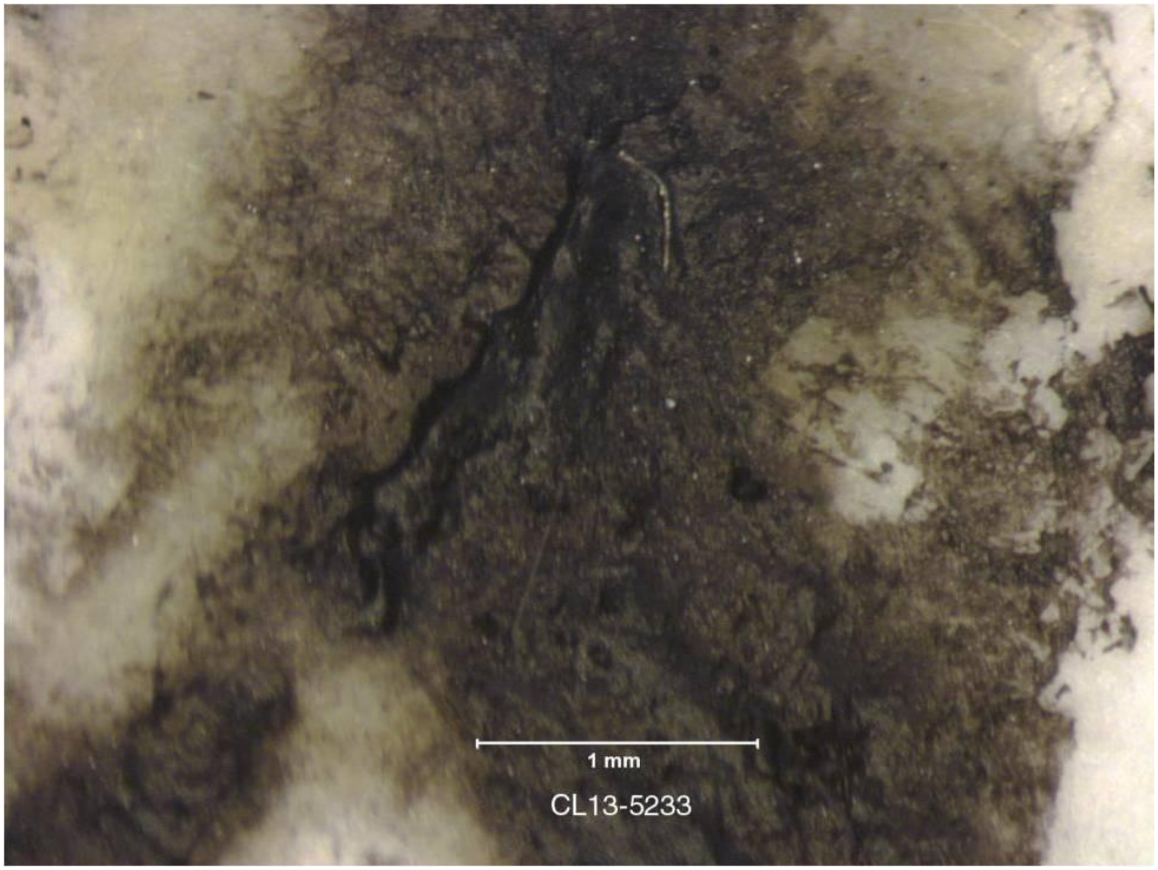
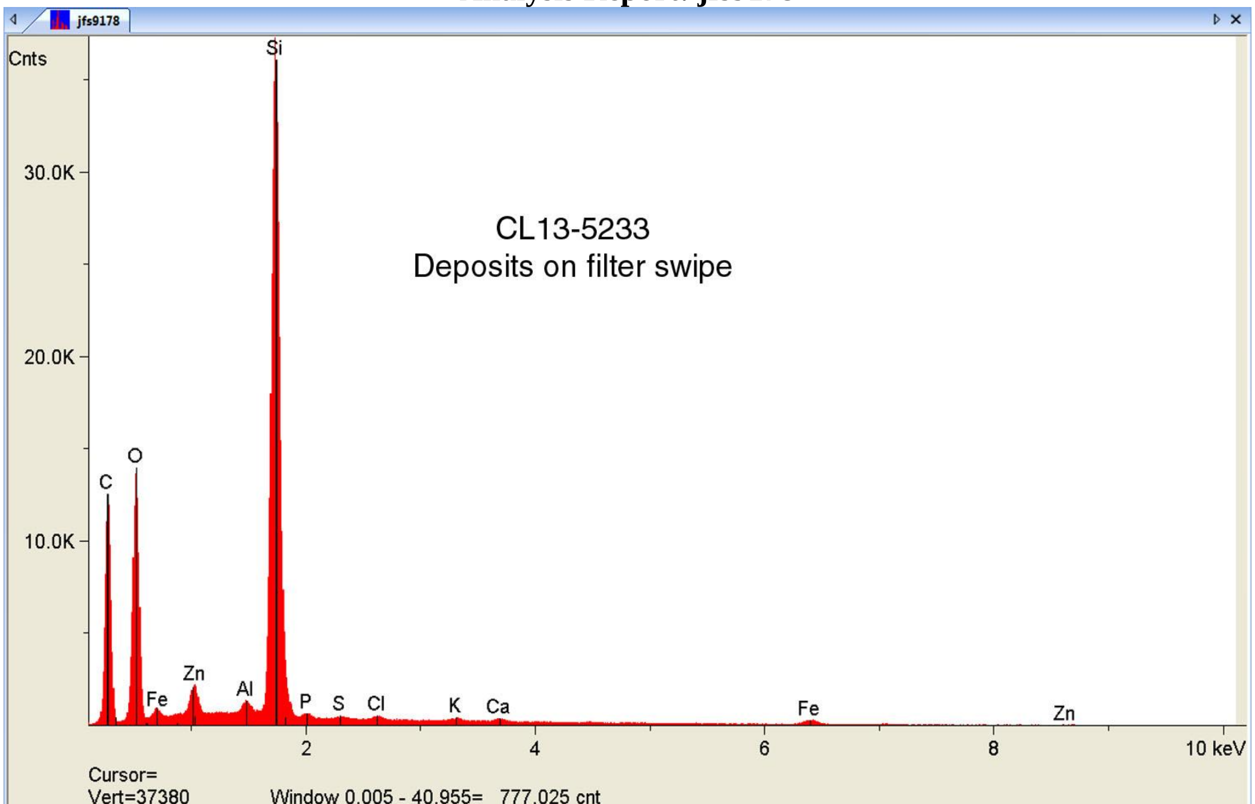


Figure 12. Filter Patch After 11,000 cycles Revealing Dark and Metallic Particles

Analysis Report: jfs9178



Elt.	Line	Intensity (c/s)	Atomic %	Conc	Units	
Al	Ka	25.68	2.12	1.99	wt.%	
Si	Ka	1,073.48	91.87	89.53	wt.%	
P	Ka	6.46	1.54	1.66	wt.%	
S	Ka	4.34	0.76	0.85	wt.%	
Cl	Ka	6.06	0.85	1.05	wt.%	
K	Ka	5.38	0.59	0.80	wt.%	
Ca	Ka	5.62	0.58	0.81	wt.%	
Fe	Ka	11.35	1.49	2.88	wt.%	
Zn	Ka	0.84	0.19	0.44	wt.%	
			100.00	100.00	wt.%	Total

kV 20.0
Takeoff Angle 23.0°
Elapsed Livetime 300.0

Note: Results do not include elements with Z<11 (Na).

Figure 13. Surface Scan jfs9178 Elemental Analysis

Testing was continued until 15,000 pump & dump cycles were accumulated on the DOT V brake fluid. When the reservoir and accumulators were drained there was evidence of particulate formation in the HPB reservoir. The particulates formed are shown in Figure 14, indicated by the ellipse, as seen in the emptied reservoir. There was not sufficient particulate formed to cause a compromise of the filter media as noted by the manufacturer in prior testing. A pipette was used to withdraw the particulate and the remaining 50-ml of fluid from the HPB reservoir. The 50-ml of fluid was filtered through a 0.7-micron glass fiber filter to capture any particles as shown in Figure 15. The large flake like particle is likely some of the thickened fluid from the HPB filter that was transferred by the pipette. The fluid prior to filtering did appear to have a grayish tint, which usually indicates black particulate is present. The filter media was examined under magnification and black particulate was present along with evidence of metallic particles as shown in Figure 16.

Figure 14. HPB Reservoir with Particle Accumulation Evident after 15,000 Cycles

Figure 15. Filtered DOT V Fluid from Reservoir after 15,000 Cycles.

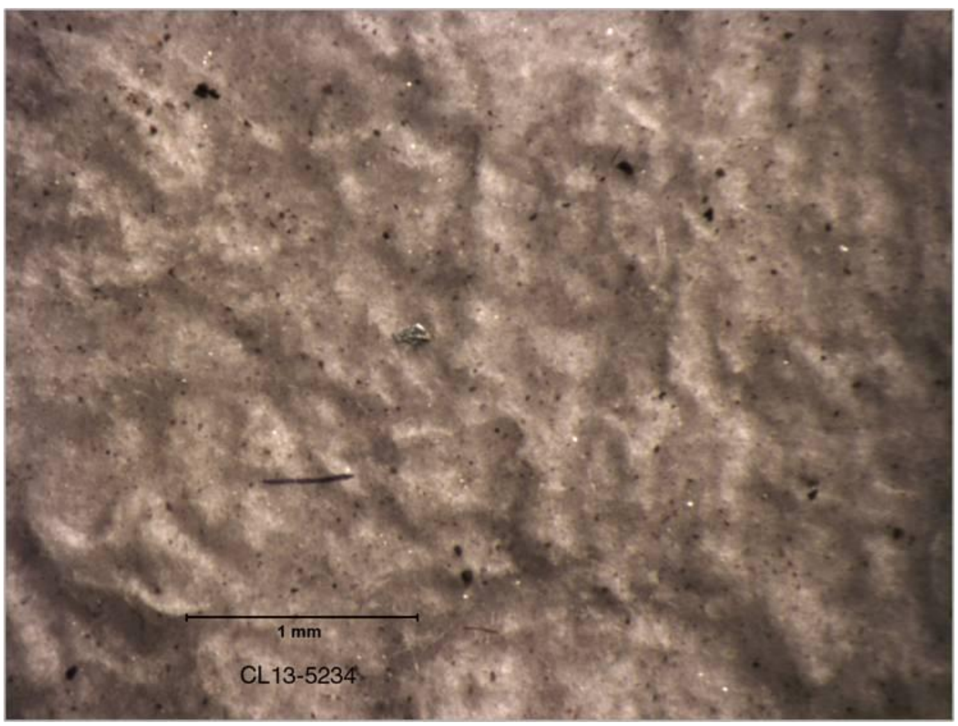


Figure 16. Magnification of Filter Media Revealing Black Particulate and Shiny Metallic Particles

In Figure 16, large and small black particles and large and small metallic particles can be seen. A backscatter SEM image of the large metallic particle is noted jsf9174 in Figure 17, with the elemental analysis of the particle shown in Figure 18. The elemental analysis of particle shows high levels of silicon and zinc. An elemental analysis scan of the filter surface, noted as jsf9175, reveals primarily silicon, as shown in Figure 19. Testing was continued because the filter media did not appear compromised.

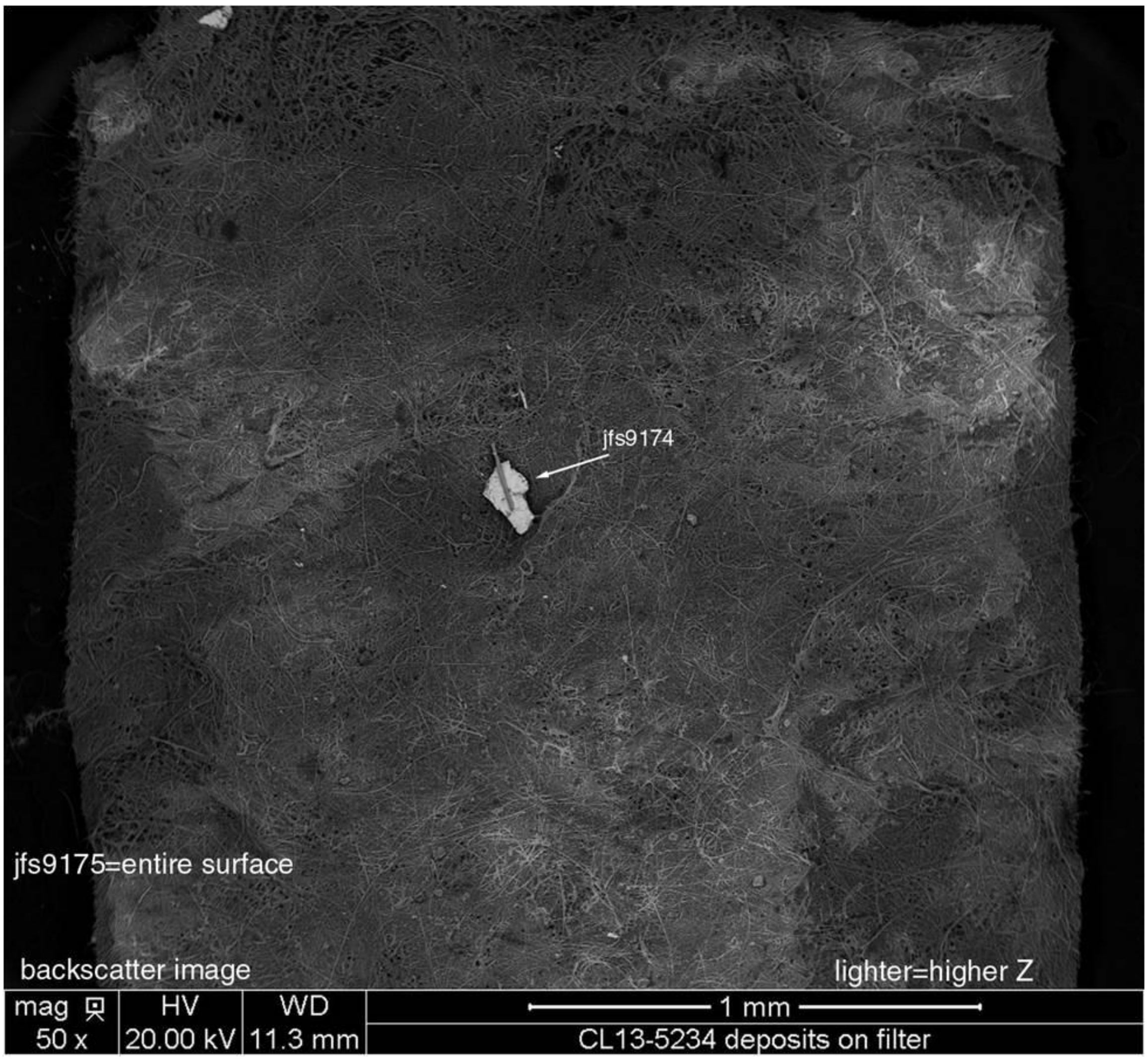
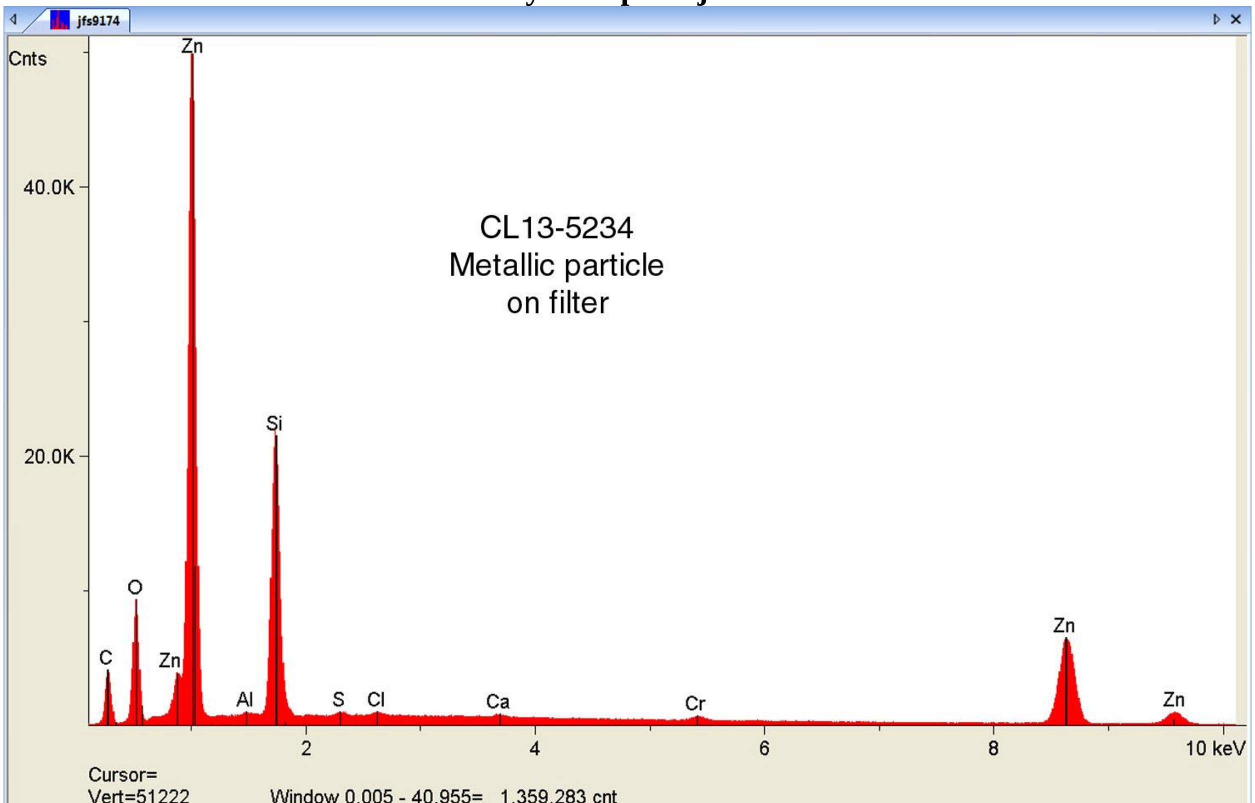


Figure 17. Backscatter SEM Image showing Elemental Analysis Scan Locations of Glass Fiber Filter

Analysis Report: jfs9174



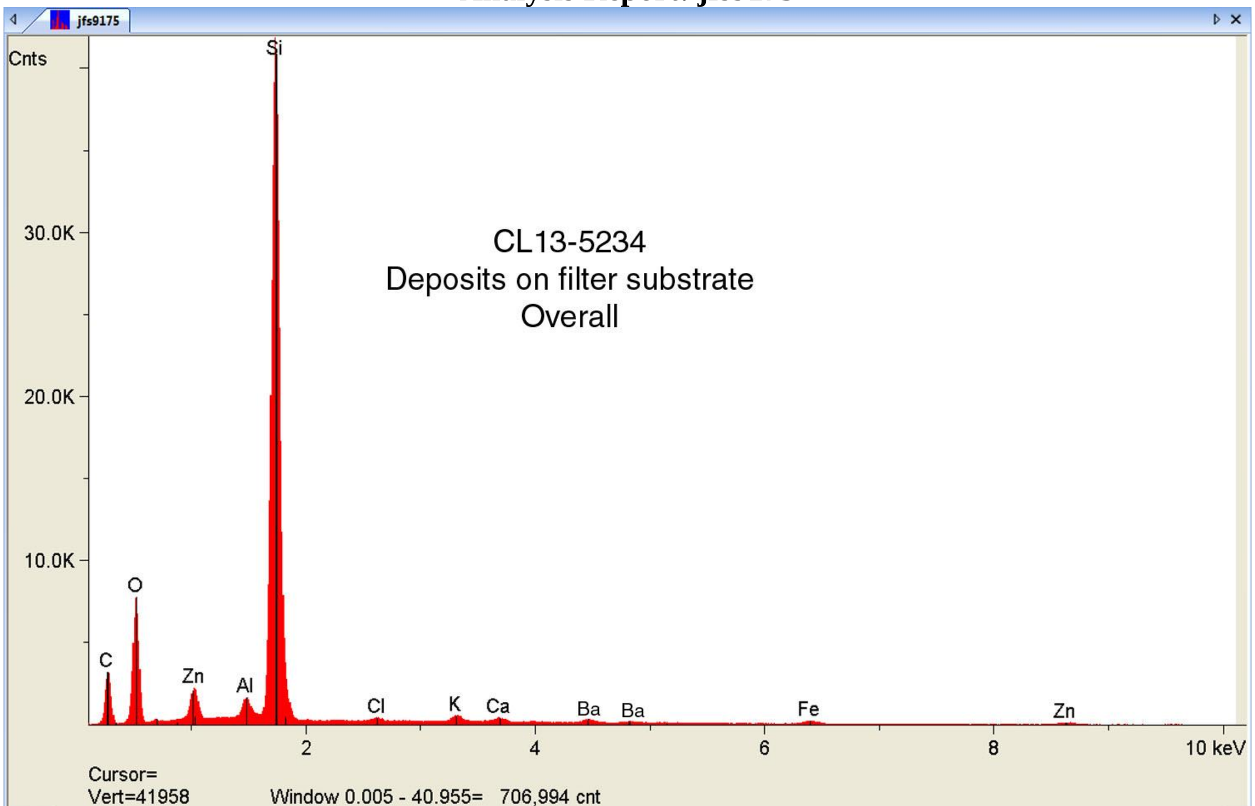
Elt.	Line	Intensity (c/s)	Atomic %	Conc	Units	
Al	Ka	6.20	0.75	0.48	wt.%	
Si	Ka	621.26	58.75	38.79	wt.%	
S	Ka	10.08	0.78	0.59	wt.%	
Cl	Ka	10.20	0.65	0.54	wt.%	
Ca	Ka	8.46	0.40	0.38	wt.%	
Cr	Ka	14.18	0.69	0.85	wt.%	
Zn	Ka	349.22	37.98	58.38	wt.%	
			100.00	100.00	wt.%	Total

kV 20.0
Takeoff Angle 23.0°
Elapsed Livetime 300.0

Note: Results do not include elements with Z<11 (Na).

Figure 18. Particle Scan jfs9174 Elemental Analysis

Analysis Report: jfs9175



Elt.	Line	Intensity (c/s)	Atomic %	Conc	Units	
Al	Ka	35.90	2.70	2.46	wt.%	
Si	Ka	1,215.52	91.97	87.21	wt.%	
Cl	Ka	6.79	0.76	0.91	wt.%	
K	Ka	13.64	1.18	1.56	wt.%	
Ca	Ka	8.64	0.72	0.97	wt.%	
Fe	Ka	8.76	0.92	1.74	wt.%	
Zn	Ka	6.63	1.23	2.71	wt.%	
Ba	La	7.39	0.53	2.46	wt.%	
			100.00	100.00	wt.%	Total

kV 20.0
Takeoff Angle 23.0°
Elapsed Livetime 300.0

Note: Results do not include elements with Z<11 (Na).

Figure 19. Elemental Scan of Filter Surface Deposits After 15,000 Cycles

Testing continued till 20,000 cycles when it was noted the filter media appeared to be collapsing. A video bore scope was used to inspect the filter media and filter integrity. Figure 20 shows one of the filter windows covered with a particulate laden viscous fluid, with wrinkling of the filter media suggesting an elevated differential pressure due to the deposition.

Figure 20. Filter Media after 20,000 Cycles with DOT V Brake Fluid.

The image shown in Figure 21 is a frame capture from the inspection video of a window of one of the two HPB filters, revealing the accumulation of deposits and viscous fluid. The heaviest accumulation of viscous fluid and deposits are shown in Figure 22 from the second HPB filter. Those shown in Figure 22 are the heaviest of the deposits noted from either of the inspection videos. Although the deposits appeared heavy, and the filter media was wrinkled due to elevated differential pressure, the filter integrity had not been compromised.

The testing indicated deposits can form with the DOT V brake fluid, however they had not yet compromised the filter integrity, nor had the deposition triggered any malfunction codes in the service control software. Deposit analysis from the earlier cycles indicated that metal particles are present within the viscous fluid, silicon particle matrix, suggesting wear is occurring somewhere in the HPB system.

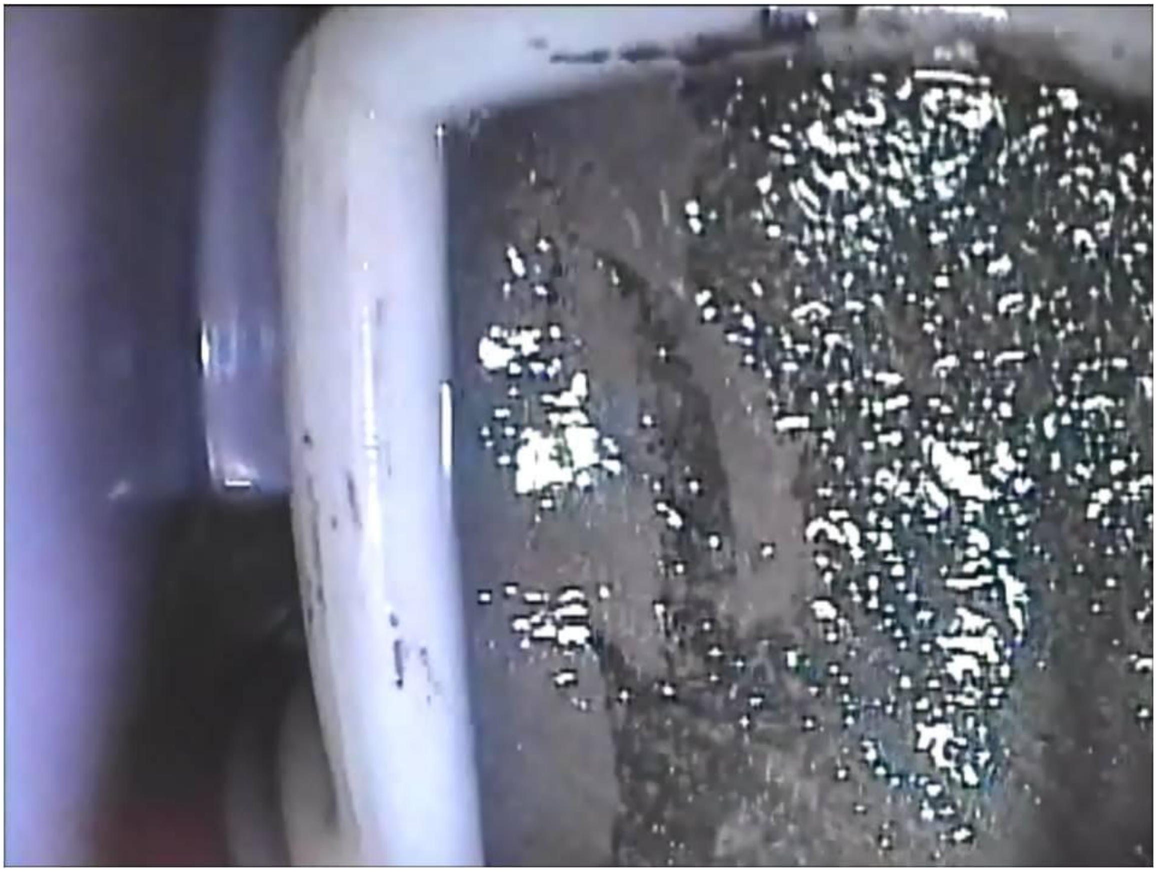


Figure 21. Image Capture From Filter Inspection Video, Revealing Deposits and Viscous Fluid Buildup

Figure 22. Heavy Deposition Noted on HPB Filter Media After 20,000 Cycles

Discussions were held with TARDEC on how to proceed with future testing and analysis. The HPB was disassembled and the pumping elements, filters, and internal components reserved for future inspections for wear and deposits. A pumping element assembly from the DOT V fluid testing is shown in Figure 23. There are new pumping elements available for condition comparison. Samples of new fluid and 20,000-cycle fluids and a filter element with accumulated residue, Figure 24, were shipped to a chemical manufacturer for analysis.

Figure 23. One of Two HPB Pump Elements From DOT V Fluid Testing

Figure 24. One of Two HPB Filter Elements with Accumulated Particulate Residue From DOT V Fluid Testing

4.2 DOT III Brake Fluid

A new HPB system was readied for a 20,000-cycle evaluation of the DOT III fluid, and the testing performed. An inspection after 11,000-cycles of the pump and dump control strategy the DOT III fluid had darkened slightly, likely due to oxidation, but there was no any evidence of deposits forming in the reservoir.

The DOT III brake fluid completed 20,000-cycles of testing without any evidence of deposition on the system filters. The filters from the DOT III fluid testing and the DOT V fluid testing have been removed from the Hydraulic Power Brake system reservoirs and are being retained for future testing and are shown in Figure 25.

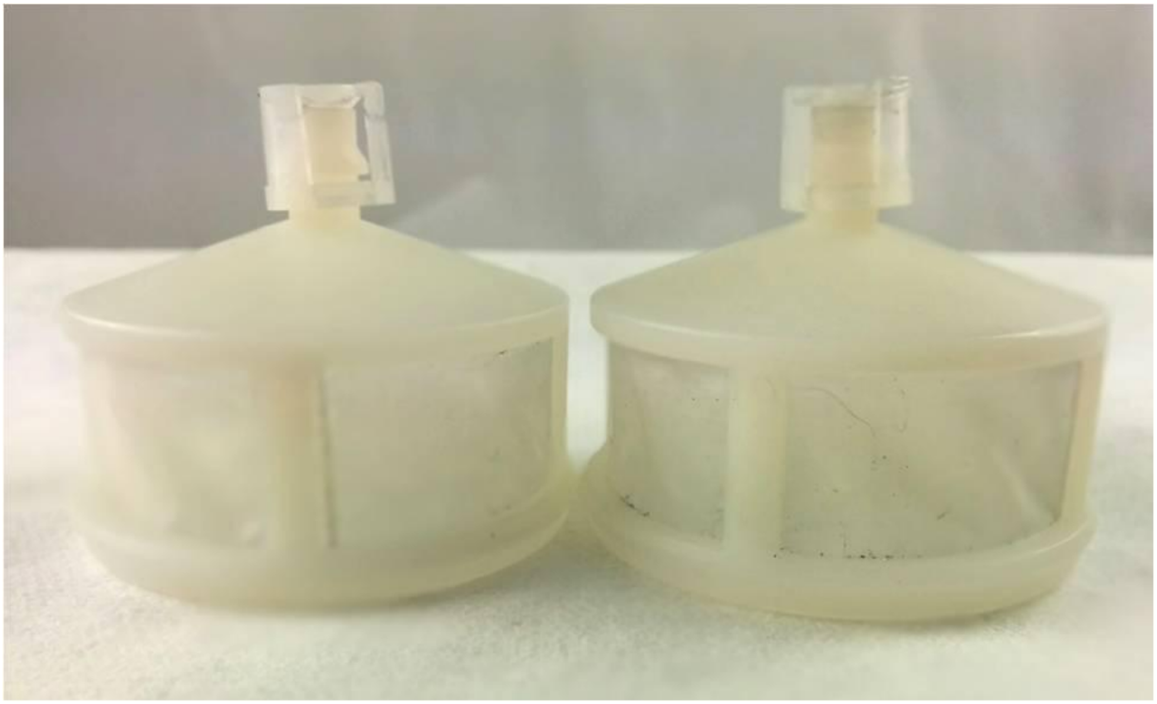


Figure 25. Two Filter Elements from 20,000-cycles of DOT III Fluid Testing

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Testing of a Hydraulic Power Brake system with MIL-PRF-46176 silicone brake fluid confirmed a manufacturer claim that the fluid was incompatible with the power brake hardware. Using a pump and dump approach that exercised the servo valves and hydraulic pumps, particulate laden fluid was evident on the internal filter at 7,000 cycles. Silicone brake fluid testing continued to 20,000 cycles where the filter element appeared caked with particles and testing terminated. The filter media had not failed, nor was the effect of failed media and particle incursions on the pumping elements and servo valves determined. Testing with DOT III fluid to 20,000-cycles did not reveal any evidence of particulate formation.

5.2 RECOMMENDATIONS

TFLRF recommends determining further analytical procedures available at SwRI for examination of the MIL-PRF-46176 residue and the new and used brake fluids. Analyses to be considered are bulk modulus, IR, HPLC, elemental analysis, GC-MS, and molecular weight. TFLRF recommends determining if HPLC columns are available for the molecular weight determinations of the new and used MIL-PRF-46176 and DOT III samples. It is recommended FTIR be used on both the new and used fluids and also the contaminant scraped from the filter.

Investigations of Hydraulic Power Brake system elastomers and pumping elements are also recommended. An investigation of the compatibility of the DOT V brake fluid with the elastomers within the power brake system could provide insight as to the source for the deposits seen. Both static seal testing for physical elastomer property changes and dynamic seal testing for wear evaluation would be recommended. Since elemental scans of thickened fluid and filter patches indicate evidence of metallic debris, an investigation into the pumping element wear, and possibly servo-valve wear would be recommended.